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Digital Microrobotics Based on Bistable Modules: Design of Compliant Bistable Structures

Qiao Chen, Yassine Haddab, Philippe Lutz, *Member, IEEE*

Abstract—In the context of micromanipulation and microassembly, we propose in this paper a new type of microrobot based on bistable modules: digital microrobots. This concept consists in building a monolithic microrobot using microfabrication technology without any assembly. It gets over the difficulties of traditional microrobots: non-linear control, integration of sensors, noise, etc. Each module contains a bistable structure and actuators. No external energy input is needed to maintain the structure in a stable position. This opens a paradigm in the microrobotics field allowing the design of various kinematics adapted to the microworld.

I. INTRODUCTION

During the last decade, significant research activities have been performed in the field of microrobotics, which deals with the design, the fabrication and the control of microrobots. These microrobots are intended to perform various tasks in the so-called Microworld (i.e. the world of submillimetric objects), in particular micromanipulation tasks of single objects (artificial or biological) for positioning, characterizing or sorting as well as for industrial microassembly. Researches already done have shown that the use of active materials to actuate microrobots gives better performances than the use of traditional actuators.

However, despite their intrinsic high resolution, these materials present some disadvantages, making the design of efficient controllers a hard task. Their behavior is often complex, nonlinear and sometimes non stationary. Closed-loop control of the microrobots requires the integration of very small sensors and the use of bulky and expensive instruments for signal processing and real-time operating. Packaging and integration of the sensors and actuators are also hard problems. This is why building multidegrees of freedom microrobots able to perform complex tasks is difficult [1].

It is necessary to design a new microrobot for meeting the challenges. We propose a concept of microrobot based on discretely-actuated modules that permit avoiding the use of sensors and eliminating non-linear control problem. In the macroscale, the most typical discretely-actuated robot is the variable geometry truss (VGT) manipulator [2] [3] [4]. (see Fig.1). This planar binary VGT manipulator consists of several modules. Each one includes three binary actuators. As a result every module has eight states (2^3).

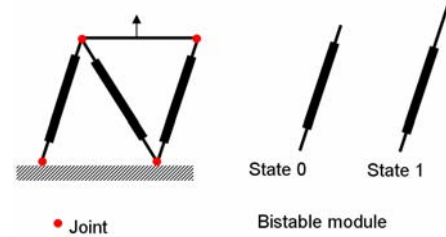


Fig. 1. A 3-bit binary VGT, "0" or "1" represents one of the states.

G.S.Chirikjian firstly presented the concept of the binary paradigm for robotic manipulators in [5]. There have been several improvements in this binary hyper-redundant manipulator concept. Much work about the calculation of the forward and inverse kinematics is done in [6] [7] [8] [9]. The Robotic Articulated Intelligent Device (BRAID) [10] is a 3-D configuration of binary actuated manipulators. There are 2^{15} states by cascading 5 modules in the 3D workspace. These binary actuated robots generally present some difficulties in the macroscale; it is hard to find a robust bistable module integrating actuators, and the overall topology design makes the inverse kinematics calculation heavy [7] [8].

In the microscale, the use of this kind of topology leads to many difficulties that limit the overall performances (repeatability, resolution, etc.). Because many rotation joints must be designed and assembled, few applications using binary actuated structures for microrobotics can be found. There are some close designs in the microworld. R.Y. Robert designed a new mechanical binary-to-analog converter [11] which was fabricated by the surface micromachine technology in 2000. One bit of this converter contains a digital input beam, an analog input beam, and an analog output beam. The digital input beam is controlled by the thermal actuator array. The output displacement can be reached by the output beam. Many converters are cascaded for accumulating the output displacement by connecting the next bit's analog input to the previous bit's analog output. In 2004, Jinqui [12] presented a curved-beam bistable mechanism for performing a relay, in which the actuator and the bistable were made in the wafer by using the bulk micromachine technology. This thermal actuator is activated by heating, and produces a force to switch on or off the curved-beam.

So, based on binary actuated robots in the macroscale and bistable compliant mechanism in the microscale, we propose an approach to perform the microfabrication of microrobots using a modular concept and an open loop control strategy. These microrobots, named "digital microrobots" are based on the design of microrobots from several "elementary

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modules”, each offers a very good repeatability and stable positions. A binary signal switches the module between the two stable states. The position of the whole microrobot is controlled by a digital word representing the state of the modules. A paradigm is opened in the microrobotics field, allowing the design of various kinematics adapted to the microworld.

This paper is organized as follows: section 2 presents the concept in the microscale. Section 3 presents the design details, from the bistable element design to the overall structure design and finally the conclusion is given in Section 4.

II. GENERAL CONCEPT

A novel principle of microrobot is proposed. The objective of this research is to design a translation and rotation axis by cascading several bistable modules that are fabricated by microfabrication technology.

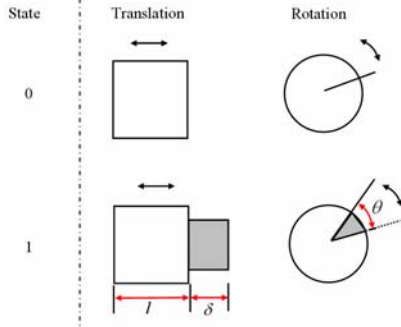


Fig. 2. Principle of bistable modules, the δ or θ stands for motion between two stable states.

The bistable mechanism is a structure or mechanism that has two stable states, Fig.2 shows the principle of bistable modules. We define state 0 or 1 respectively as one of the two stable states. Between these two stable states there are motions of translation δ or rotation θ . The bistable mechanism is switched between these two stable states by an external force, and no external energy input is needed for keeping the stable state. Many applications of this structure can be found in our daily life, for example, the light switch, the slider cell phone, etc.

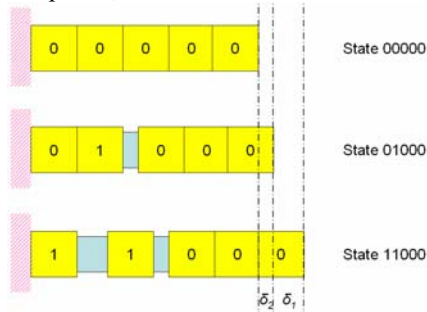


Fig. 3. An example of a bistable structure.

Using several cascaded bistable modules increases the numbers of logical states (see Fig.3). We will have an accumulation of the discrete displacement (δ) or discrete rotation (θ) by switching the different bi-stable modules, so a

displacement along the axis will be reached. As shown in Fig.3, five bistable modules are cascaded. The initial state is 00000, if the states are set as 01000, we have a displacement of δ_2 , or if the states are set as 11000, a displacement of $\delta_1 + \delta_2$ is reached. The accumulation of angle could be also obtained with the same principle. The numbers of reachable location depend on the displacement δ of the bistable module.

Although only a discrete area can be reached, the number of logical states is an exponent function of the bistable structure number.

Total logical states = 2^n , n : the number of bistable modules.

For example, there are 1024 logical states for 10 bistable modules. If we define a configuration of every bistable module's displacement as: $d, 2d, 4d, \dots, 512d$, where d is the minimum displacement needed, the maximum obtained displacement is:

$$D = d \times [1, 2, 4, 8, 16, \dots, 512] \times [1, 1, 1, 1, \dots, 1]^T$$

$$= d \times \sum_{i=1}^{10} 2^{i-1} = 1023d \quad (1)$$

Where D is the maximum displacement.

The minimum displacement d represents the resolution limited by the microfabrication.

For example, if $d = 1\mu\text{m}$, in order to have a displacement of $498\mu\text{m}$; the corresponding binary states are 011110010.

The position of the tip of the digital microrobot is represented by a binary word that could be used as a control instruction. Table 1 is based on information from [1][11][12][13][14][15], we give a detailed comparison between the characteristics of present microrobots and the proposed binary microrobots.

TABLE I
A COMPARISON BETWEEN PRESENT MICROROBOTS AND DIGITAL MICROROBOTS

Characteristic	Present microrobots		Digital Microrobots
Actuation approach	Continuous actuation	Discrete actuation	Discrete actuation
Size	Medium	Medium	Small (microfabrication)
Cost	High	Medium	Low
Control	Closed loop Non-linear control	Closed loop control	Open loop (no sensors needed)
Energy consumption	High to medium	High to medium	Low
Sensitivity to noise	High	Low	Low
Use of sensors	Yes	Yes	No
Displacement	Continuous	Discrete	Discrete

This novel concept shows many advantages. Good repeatability and accuracy are obtained thanks to the mechanical performances of the bi-stable modules. Moreover

neither proprioceptive sensors nor bulky and expensive instruments are needed. Low power consumption can be obtained because external energy is not needed to maintain the modules in a given state but only during the transition phases, and the immunity to noise and environment changes is improved. Using the parallel control of the modules, fast displacements can be obtained. Microrobots can be built in great quantities (and potentially at low cost) with microfabrication. Using bistable structures give an approach that turns the difficulties of non-linear control into mechanical structure design. Digital microrobotics takes advantage of microfabricated mechanical bistable structures and open-loop digital control to offer a unique method to build efficient microrobots. However, some drawbacks exist: accumulation of errors, limited load, and discrete reachable area.

The bistable structure and its actuators are two essential components for building a bistable module. The next section presents a design of bistable modules.

III. DESIGN

The objective is to design a translation axis by cascading several bistable modules. In this paper we focus on the translation. Before designing the modules, it is necessary to take into account the microfabrication process because it strongly constrains the design. The rules of MEMS design are respected: the etching minimum width, the etching accuracy, etc.

The design steps are organized as follow: first, the fabrication process is defined for the choice of material and dimension limit, then the bistable module is designed, and finally, the overall structure is checked. If the overall structure is not suitable for this process, we go back to redesign the bistable module, until it is satisfied.

A. Bistable compliant structure design

An elastic deformed structure usually goes back to its original shape after unloading the applied force, but some structures go to another position. The latter behavior is so called bistable structure. This type of structure shows similar characteristics between force and displacement or between elastic deformation energy and displacement.

Many bistable structures were fabricated through MEMS technologies [13] [14] [15] [16]. One of them has been widely studied: the curved-beam bistable mechanism. This compliant mechanism does not need any assembly such as pins or sliders. Moreover it can be fabricated by batch processing. Taking into account the limit of the bulk micromachine technology available in our clean room, and also a good bistability, the dimensions of the design are shown in Fig.4.

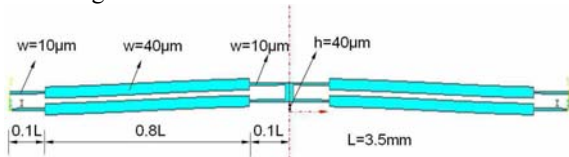


Fig. 4. Two curved beams.

According to the pseudo-rigid-body model [17] [18], a calculated model is presented in Fig.5. The bistability is determined by torsional spring stiffness ks , the elastic beam stiffness kb , and the initial height of the curved beam h .

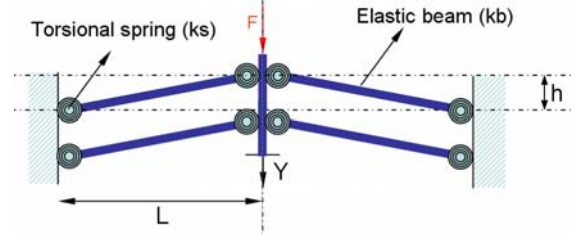


Fig. 5. An equivalent model for bistable beam

The angle θ of torsional spring and the deformation x of the elastic beam can be expressed as a function of the vertical displacement Y , which is caused by an external force F .

$$x = (\sqrt{L^2 + h^2} - \sqrt{L^2 + (h-Y)^2}) \times 0.8 \quad (2)$$

$$\theta = \tan^{-1}\left(\frac{h}{L}\right) - \tan^{-1}\left(\frac{h-Y}{L}\right) \quad (3)$$

L , h and Y are shown in Fig. 5.

The strain energy U can be derived by the torsional spring stiffness ks and the elastic beam stiffness kb :

$$U = 8 \cdot \frac{1}{2} \cdot ks \cdot \theta^2 + 4 \cdot \frac{1}{2} \cdot kb \cdot x^2 \quad (4)$$

$$F = \frac{\partial U}{\partial Y} = 8 \cdot ks \cdot \theta \frac{\partial \theta}{\partial Y} + 4 \cdot kb \cdot x \frac{\partial x}{\partial Y} \quad (5)$$

$$F = \frac{\partial U}{\partial Y} = 8 \cdot ks \cdot \left(\tan^{-1}\left(\frac{h}{L}\right) - \tan^{-1}\left(\frac{h-Y}{L}\right) \right) \cdot \frac{1}{\left(1 + \left(\frac{h-Y}{L}\right)^2\right)L} + 4 \cdot kb \cdot \left(\sqrt{L^2 + h^2} - \sqrt{L^2 + (h-Y)^2} \right) \cdot \frac{(h-Y)}{\sqrt{L^2 + (h-Y)^2}} \quad (6)$$

The F 's High orders of the Taylor series about Y are ignored. The two stable states Y_s and the instable state Y_i are obtained for $F=0$.

$$Y_s = 0$$

$$Y_s = \frac{10 \cdot ks \cdot h + 6 \cdot kb \cdot L^2 \cdot h + 2 \sqrt{kb^2 \cdot L^4 \cdot h^2 - 50 \cdot ks^2 \cdot L^2 - 20 \cdot kb \cdot L^4 \cdot ks}}{10 \cdot ks + 2 \cdot kb \cdot L^2}$$

$$Y_i = \frac{10 \cdot ks \cdot h + 6 \cdot kb \cdot L^2 \cdot h - 2 \sqrt{kb^2 \cdot L^4 \cdot h^2 - 50 \cdot ks^2 \cdot L^2 - 20 \cdot kb \cdot L^4 \cdot ks}}{10 \cdot ks + 2 \cdot kb \cdot L^2}$$

In our case, ks and kb can be calculated according to the pseudo-rigid-body theory.

$$ks = \frac{EI}{0.1L} \quad (7)$$

$$kb = \frac{EA}{0.8L} \quad (8)$$

E : Young's modulus

I : Inertial moment

A : Section area

A finite element analysis (FEA) is made by using the commercial FEA software ANSYS. The result from the model and the FEA are presented in Fig.6 and Fig.7.

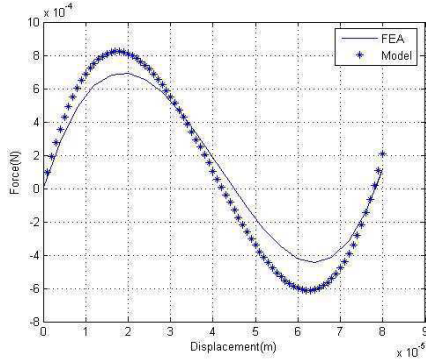


Fig. 6. Force (F) and displacement (Y) characteristic.

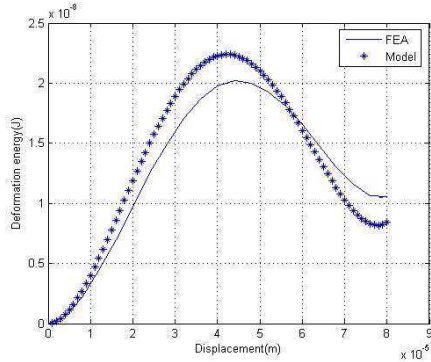


Fig. 7. Deformation energy (U) and displacement (Y) characteristic.

This model shows a little bigger stiffness than FEA because of the simplification of the torsionnal spring model but it can be considered as a sufficient approximation.

So, for switching from a stable state to another, a microactuator which can produce a force of 0.7mN and a stroke of 50 μ m is needed.

B. Actuator design

The potential candidates could be piezoelectric, thermal, electrostatic and shape memory alloy (SMA) actuators. Due to the use of the bulk micromachine technology, piezoelectric actuators and SMA actuators are difficult to integrate. The calculation of the electrostatic actuator shows that it takes a lot of space for reaching the required force. So we decided to use thermal actuators. The work of Jinqui [12] gave an example of using the thermal actuator with the bulk micromachine technology.

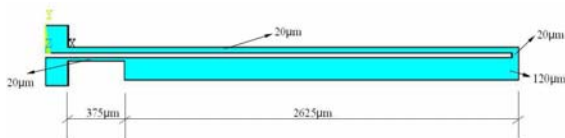


Fig. 8. A typical thermal actuator

Based on the models described in [15] [16], Fig. 8 shows the dimensions of the thermal actuator we designed. The commercial FEA software offers a structural-thermoelectric

tetrahedron element (SOLID227) which permits us to make coupled electric-thermo-mechanic analyses. We took into account all the thermal effects: the conduction, the convection, and the radiation (see Fig. 9).

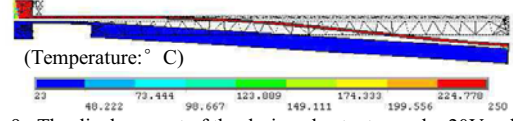


Fig. 9. The displacement of the designed actuator under 20V voltage.

The needs of the bistable structure are reached. Indeed, this actuator gives a displacement of 60 μ m and a force of 2mN under a driving voltage of 20V. According to [19] [20], the thermal convection and radiation can be neglected in the microscale, so the heat is accumulated in the structure. There is 12mJ energy needed for every switching operation. Thanks to good thermal conductivity of the silicon, it is transferred quickly into the substrate.

Two pairs of thermal actuators are used for switching between the two states.

C. Stop block design

In order to guarantee the repeatability of the two stable positions, stop blocks are considered (see Fig.10 and 11). They limit the displacement of the shuttle.

Due to the monolithic microfabrication of the overall module, a first activation is necessary in order to insert the shuttle between the two stop blocks. During this first activation, one should be careful of the compliant parts of the shuttle (see Fig. 11).

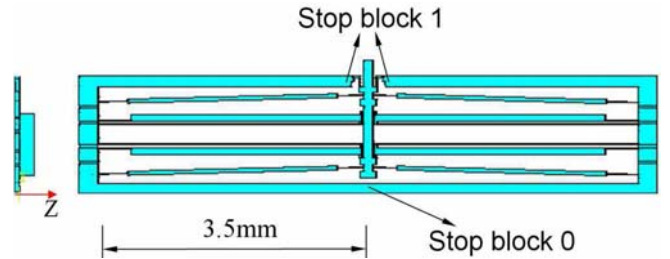


Fig. 10. One bistable module: four thermal actuators, two bistable beams, stop blocks, and a frame.

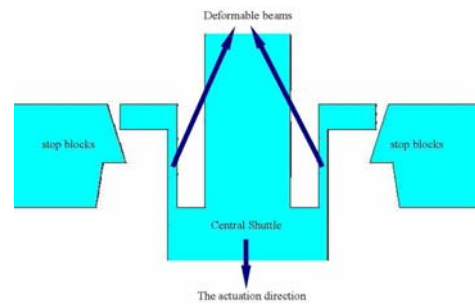


Fig. 11. The stop block of the state 1

So the bistable module [Fig.10] which contains two bistable beams, four thermal actuators, a frame and a shuttle is finished. In the next section the overall design will be discussed. A distance of $10\mu\text{m}$ between the two states is set by these two stop blocks. The mechanical robustness of the stop block define the error of the bistable module.

D. Overall design

Because the overall structure is composed of a large number of similar bistable modules, it is very important to consider the relationship between the overall structure and the bistable module. Firstly, two cascaded bistable modules are considered (see Fig.12). Since the two curved-beams will support all the structure weight in the first bistable module, it is necessary to study the gravity effect in the structure.

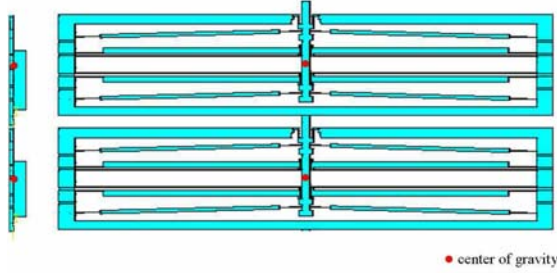


Fig. 12. Two cascaded bistable modules.

In order to find the out-plan stiffness caused by gravity. We performed a calculation model presented in Fig.13.

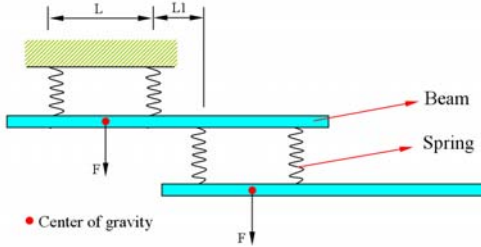


Fig. 13. Two cascaded bistable modules.

In this calculation model, the two bistable curved beams are considered as two springs, and the actuators and the frame are considered as a rigid beam. Only the spring causes a flexion. The gravity center of every bistable module is located in the middle of the two springs.

For n bistable modules, we simplify the model as in Fig.14. The moment $(M(n^2-n)/2)$ and force (nF) are the equivalent moment and force of the n bistable modules which are applied on the first bistable module. The out of plane flexion can be obtained:

$$\delta_n = \frac{nF}{k} + \frac{M(n^2-n)}{2Lk} \left(\frac{0.5L + L1}{0.5L} \right) \quad (9)$$

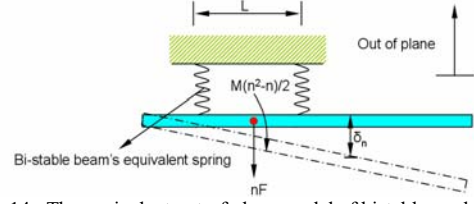


Fig. 14. The equivalent out-of plane model of bistable module.

The spring is a variable section cantilever beam, of which stiffness k can be determined by a classic cantilever model:

$$k = 2 \times \frac{EI}{l^3} \times \frac{1}{\frac{0.1^3 + 0.1^3}{3} + \frac{0.9 \times 0.1^2}{2} + \frac{0.8^3 + 0.1 \times 0.8^2}{10}} = \frac{38EI}{l^3} \quad (10)$$

Where:

E : Young's modulus

I : Inertial moment

l : Length of the cantilever beam

The comparison of the tip's flexion between model and the FEA is presented in table 2 for n cascaded bistable modules.

TABLE 2
TIP'S FLEXION COMPARISON OF MODEL AND FEA

n	Model (μm)	FEA (μm)
1	0.24	0.2
2	2.1	1.9
3	14	12
4	38	35

The tip's flexion is accumulated with the increase of the bistable modules. The analysis shows that there isn't much stress in the first bistable module. Nevertheless, the tip of the structure has an important flexion. According to the formula 9 and 10, we can obtain:

$$\delta_n \propto \left(\frac{1}{k} \right) \propto \left(\frac{1}{I} \right) \propto \left(\frac{1}{h^3} \right) \quad (11)$$

According to the formula 11, the tip's flexion could be reduced with the increase of the thickness of the structure. In our case, the tip's flexion is $2\mu\text{m}$ with a thickness of $100\mu\text{m}$. This flexion is neglected.

IV. CONCLUSION

In this paper, we have presented the concept of a digital microrobot which contains several cascaded bistable modules. Every module consists of two curved beams and four thermal actuators. The stop blocks are designed to limit the displacement between the stable states for a good repeatability. The bistable structure has been designed to obtain a good repeatability, symmetric force-displacement curve and the possibility to build cascaded structures. The choice of thermal actuators meets the needs of the bistable structure in term of force, displacement, and easy integration. No external energy input is needed to maintain the structure in a stable position.

The batch microfabrication permits us to fabricate a monolithic structure without any assembly. This new digital microrobot offers several advantages that overcome the problems of traditional microrobots.

We are now characterizing the behavior of the microfabricated bistable structures.

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